On the extraction of positive and negative ions from electron-beam-generated plasmas

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The results of investigations using pulsed, electron-beam-produced plasmas in Ar/SF_6 mixtures are reported. Positive and negative ions were extracted during the active phase of plasma production using a low-frequency, low-voltage bias applied to the sampling electrode. Time-averaged energy distributions, accumulated over several extraction periods, were employed to investigate the flux of both the positive and negative ions. The extraction of negative ions in large quantities suggests the formation of ion–ion plasmas, and the time-averaged energy distributions are in agreement with estimates of sheath formation at the biased electrode. [DOI: 10.1063/1.1595155]

In ion–ion plasmas, negative ions are the principal negative charge carrier, with a density that typically exceeds the electron density by several orders of magnitude.[1,2] With a negligible electron population, the electric fields governing charge particle flow from the plasma are essentially absent, allowing both positive and negative ions to be extracted in approximately equal amounts. This is in contrast to conventional electron–ion plasmas, in which the negative ions are largely confined to the plasma by the sheath potential. Kanakasabapathy *et al.*[3,4] have shown that alternating fluxes of positive and negative ions can indeed be extracted from ion–ion plasmas formed in the afterglow of a pulsed discharge by applying a low-frequency bias to the substrate.

In previous work,[5] we demonstrated that comparable fluxes of positive and negative ions can be extracted from electron-beam-generated plasmas produced in Ar/SF_6 mixtures also using a low-frequency, sinusoidal bias applied to the sampling electrode. Both ion species were extracted during the active phase of pulsed plasma production, thereby not limiting the flux of negative ions to a particular phase of plasma production. Such extraction could be useful in materials processing. In the fabrication of microelectronic devices, for example, the delivery of anisotropic fluxes of both positive and negative ions to substrate surfaces is thought to alleviate some of the damage associated with surface charging.[3,6,7] Since plasmas produced by electron beams can generate fluxes of positive and negative ions during all phases of plasma production, continuous processing with mainly positive and negative ions is possible.

The production of large negative ion densities in electron-beam-generated plasmas formed in halogen-based gases occurs because plasma electron temperatures are inherently low ($T_e < 1.0$ eV) with this method of plasma production,[8–10] and hence electron attachment rates[11] are large. For SF_6 in particular, the attachment cross section increases by several orders of magnitude as the electron energy approaches zero.[12] The attachment rate becomes comparable to the ionization rate and, with significant SF_6 concentrations, most electrons created are converted to negative ions, thus forming an ion–ion plasma. By contrast, in conventional pulsed discharges, plasma electrons are relatively hot during the ionization phase, lowering attachment, and precluding ion–ion plasma formation. In the afterglow, the electron temperature falls and ion–ion plasmas can form.[2,13,14]

In an ion–ion plasma in which the ions are identical with the exception of charge, the plasma potential is zero and ions are evenly distributed throughout the plasma. The delivery of cold ions to an electrode (or substrate) surface necessitates the application of an extraction bias. This bias, however, changes the character of the ion–ion plasma at the plasma/electrode boundary, and in particular breaks the homogeneous distribution of positive and negative charges, causing a sheath to form. Midha and Economou[6] have simulated ion–ion plasmas under the influence of an extraction bias, and have found that for geometrically equivalent electrodes and identical positive and negative ions, the applied bias is evenly distributed across the sheaths at the powered and grounded electrodes. The sheath voltage as well as the bias frequency and gas pressure will determine the incident ion energies. In this work, we extend our previous measurements to include time-averaged energy distributions of positive and negative ions accumulated over several extraction periods, and then use those distributions to infer the properties of the sheaths formed as a result of the applied bias.

The experiments were performed in the Naval Research Laboratory's large-area plasma processing system, which utilizes a magnetically collimated electron beam to ionize a background gas. The experimental apparatus, schematically represented in Fig. 1, has been previously described.[5] The stainless steel chamber has a base pressure of 10^{-8} Torr and is surrounded by coils that produce a solenoidal field measuring 150 Gauss along the chamber axis. The electron beam is extracted from a 25-cm-wide linear hollow cathode and enters the experimental region through a 1-cm slot in a grounded anode. The beam cross section is set by the slot and maintained by the magnetic field as the beam propagates across the 50-cm chamber. For all measurements reported here, each beam pulse was 1 ms long with a repetition rate of 50 Hz, and the beam energy was nominally 2 keV. The par-

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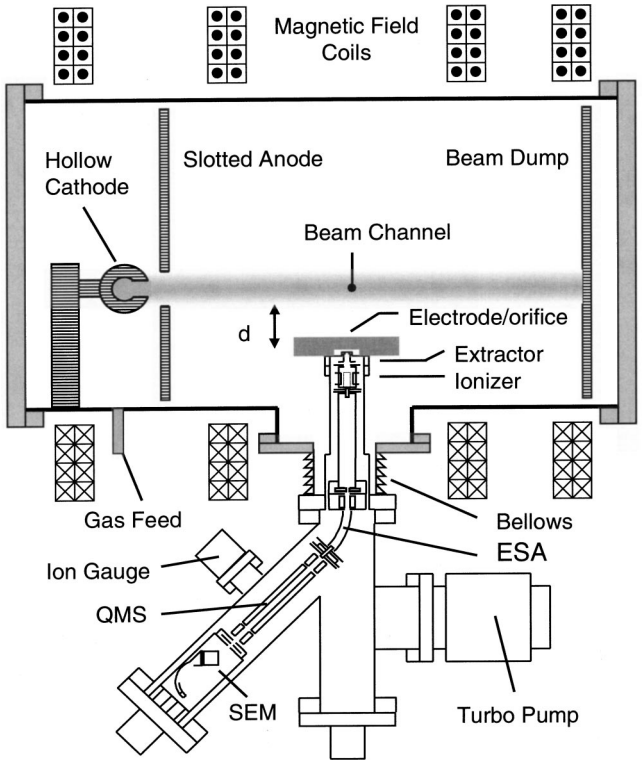

FIG. 1. Schematic diagram of the chamber and the plasma probe. The probe consists of an energy analyzer (ESA) in series with a mass spectrometer (QMS).

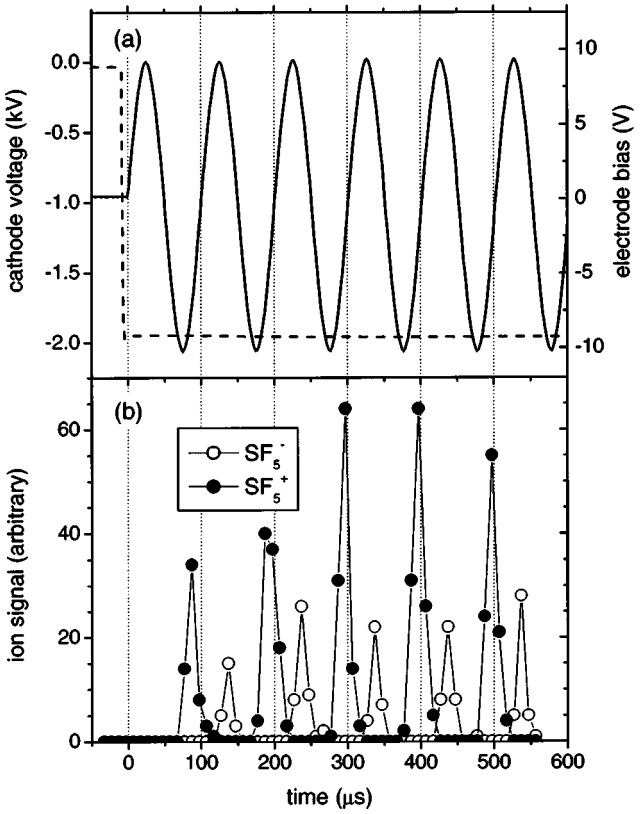

FIG. 2. (a) The applied cathode voltage (dash) and the low-frequency extraction bias (solid) applied to the electrode. (b) The extracted SF_5^+ (solid circles) and SF_5^- (open circles) signals.

tial pressures of Ar and SF_6 were each 35 mTorr (70 mTorr total pressure).

Ion fluxes and energy distributions were measured at a 5.7-cm-diameter stainless steel electrode located 1 cm from the beam edge and near the center of the plasma sheet. The measurements were performed using a Hiden EQP 300 Plasma Probe (Fig. 1), which consists of an electrostatic ion-energy analyzer (ESA) in series with a quadrupole mass spectrometer (QMS). The probe is differentially pumped and maintained at pressures less than 5×10^{-7} Torr for all operating conditions. Ions enter the EQP through a 50-μm diameter aperture located in the center of the electrode and are energy and mass filtered prior to detection by a channeltron secondary-electron multiplier (SEM). For all measurements, the passband of the ESA was fixed at ±0.5 eV. The probe has not been calibrated to determine the absolute flux.

Time resolution was achieved using a scanning or fixed gate on the EQP output (SEM), as previously described.[15] The gate of the SEM signal was scanned in equal increments to obtain the temporal flux measurements. For the energy distributions, the gate remained fixed so that the distributions were accumulated during the selected time window. For both methods, the signal was accumulated over several hundred pulses to achieve a reasonable signal-to-noise ratio.

The ability to extract fluxes of both positive and negative ions from the plasma during the active phase of plasma production is demonstrated in Fig. 2. There is a broad range of ion species in this system[5] with SF_5^+ and SF_6^- being the dominant cations and anions, respectively. In Fig. 2, species of equal mass were chosen to avoid errors associated with time-of-flight differences within the EQP. The active phase, defined by the cathode pulse, is shown for times up to 600 μs in Fig. 2(a) along with the sinusoidal extraction bias applied to the electrode (10 kHz, ±10 V). The SF_5^+ and SF_5^- signals shown in Fig. 2(b) were collected during a 10-μs-wide gate that was scanned in steps of 10 μs.

Shown in Fig. 3 are the time-averaged energy distributions of the extracted SF_5^+ and SF_5^- ions collected over the entire active phase, which includes 10 extraction cycles for each species. The distributions are presented in their raw form (i.e., as a function of energy analyzer voltage), since this technique of ion extraction does not allow for an easy conversion from voltage to energy. For a dc biased electrode, the energy scale is shifted from the voltage scale by the

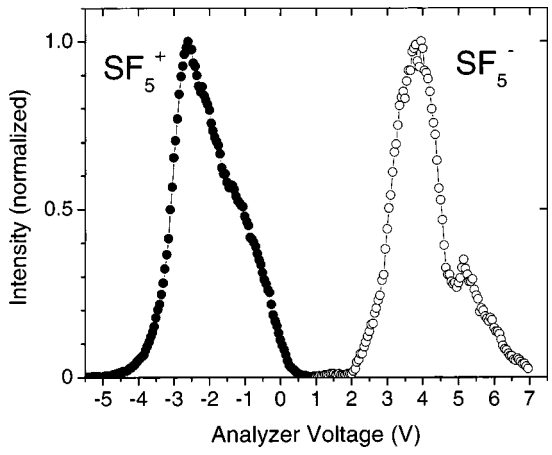

FIG. 3. The time-averaged ion energy distributions of the positive and negative ions extracted during the active glow; SF_5^+ (solid circles) and SF_5^- (open circles).

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magnitude of the electrode bias.[16] The difficulty in determining the energy scale in this work is introduced by accumulating the distributions over a time-varying electrode bias,[17] and will be discussed subsequently.

First, consider sheath formation resulting from the extraction of ions from the plasma. Assume the plasma potential is zero without a bias and the application of a time-varying bias $V_b(t)$ produces a plasma potential that varies roughly as $V_b(t)/2$. The sheath thickness can be estimated using $s(t)=743[2V_s(t)/n_i]^{1/2}$, where s is in centimeters. $V_s(t)=V_b(t)/2$ is the sheath potential in volts, and n_i is the ion density at the sheath edge in cm^{-3}. The plasma density is not directly known, but should be considerably lower than the $\sim 10^{11}$ cm^{-3} densities previously measured[8] in electron-beam-generated plasmas. The ion density is lower in ion–ion plasmas because of large ion–ion recombination rates. Moreover, the application of a bias further enhances the loss of ions since a significant fraction of the density can be extracted.[6] Assuming $n_i \geqslant 10^9$ cm^{-3} and $V_s=V_b/2 \leqslant 5$ V, the sheath thickness could extend to as much as ≈ 0.7 mm. Note that for this density, the ion plasma frequency is $\geqslant 500$ kHz and fast compared to the applied bias frequency (10 kHz), so that the sheath oscillations should easily track the applied bias.

Consider now the energy gained by ions that have traversed the driven sheath. Without collisions, ions would realize the full plasma potential, while collisions would decrease the energies toward zero, resulting in energy distributions ranging from 0 to $e|V_b|/2$ at any given instant. The corresponding voltage distribution, measured by the energy analyzer, would extend between V_b and $V_b/2$. For distributions accumulated over many extraction cycles, the temporal variations in V_b produce a spread in the voltage distribution ranging from 0 to $\pm V_{\max}$, where $V_{\max}=10$ V is maximum applied bias, and have no direct correlation to energy.[18]

The distributions of Fig. 3 have two notable features. First, the breadth of each distribution is approximately 5 V rather than 10 V, and second, the distributions are not symmetric about the origin. The former suggests that the ions are nearly collisionless since the breadth of each distribution is approximately $V_b/2$. For energies above 0.5 eV, the ion mean free path is estimated[19] to exceed 1 mm and thus to exceed the maximum sheath thickness (0.7 mm), making collisionless transport through the sheath likely. The lack of symmetry is not fully understood but probably results from differences in electrode geometry and from variations in the ion transport properties. In particular, the absence of an opposing ground electrode introduces some uncertainty in the size of the ground sheath and the average masses of the positive and negative ions are not equal. As a result, the applied bias is not evenly distributed between the ground and powered sheaths. Furthermore, in addition to the short-term variations in the sheath potential due to the sinusoidal bias, the distributions include longer-term variations resulting from the slow evolution of the plasma. Despite these uncertainties, the data indicate that the voltage drops across both sheaths are comparable and that the ions realize most of that voltage. Ion–ion etching should thus be feasible with these plasmas although how these measurements scale with the applied bias frequency and voltage would be useful.

In summary, positive and negative ions were extracted during the active phase of a pulsed, electron-beam-generated plasma produced in Ar/SF_6 mixtures using a low-frequency, low-voltage bias applied to an electrode located adjacent to the plasma. The extracted flux of both positive and negative ion species were measured and are in reasonable agreement with simple estimates of the sheath formation in ion–ion plasmas. Although further investigation is required, the results suggest these plasmas could be useful in materials processing applications that would benefit from a flux of predominately positive and negative ions.

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